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EVAPORATION AND CONDENSATION HEAT TRANSFER COEFFICIENTS FOR A HCFC-124/HCFC-22/HFC-152a BLEND AND CFC-12

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ABSTRACT

Experimental heat transfer coefficients are reported for a ternary refrigerant blend composed of 40% HCFC-124, 36% HCFC-22, and 24% HFC-152a. This blend is a possible substitute for CFC-12 in vapor compression refrigeration cycles. Two-phase heat transfer coefficients were determined for the pure blend and CFC-12. The experiments were conducted over a mass flux range of 125 to 400 $\frac{kg}{m^2 s}$. The heat transfer coefficients were determined in a horizontal smooth tube 3.66 m long with an inside diameter of 8.0 mm. Heat transfer coefficients for the blend were found to be 12 to 25% higher for evaporation and 12 to 30% higher for condensation when compared at similar mass fluxes. The heat transfer coefficients for the blend and CFC-12 were also compared at flow rates that are more representative of those that will be found in actual systems. Comparing a refrigeration cycle for the the blend and one for CFC-12 that supply similar cooling capacities shows that the blend has a lower flow rate in the evaporator and condenser because the enthalpy of vaporization is higher. At a similar cooling capacity in an evaporator, the ratio of the blend to CFC-12 heat transfer coefficients for the same tube diameter is 0.88 to 1.0, while at a similar heating capacity in a condenser the ratio is 0.98 to 1.05.

INTRODUCTION

Large-scale reductions in CFC-12 use require that suitable replacements be found. Replacement refrigerants fall into two categories: refrigerant substitutes, where they are used with minor or no changes to presently designed equipment, or long-term replacements, where the equipment is redesigned for optimal operation with the replacement refrigerant. For example, HFC-134a, with its zero-ozone-depletion potential, has been discussed as a replacement that will probably require redesign of CFC-12 systems. A possible solution to both problems, particularly the need for a substitute refrigerant for CFC-12 that can be implemented immediately, is a ternary refrigerant blend composed of 36% HCFC-22, 24% HFC-152a, and 40% HCFC-124. This blend offers the advantages of thermodynamic properties similar to those of CFC-12 and compatibility with some commonly used lubricants, such as alkylbenzene oils.

Research was conducted to determine the heat transfer coefficients of the refrigerant blend under conditions similar to those found in refrigeration system condensers and evaporators. Heat transfer coefficients for CFC-12 were also measured for comparison purposes. These experimental heat transfer coefficients were determined with a rig capable of testing refrigerants during single-phase flow, evaporation, and condensation. This paper briefly reviews the main components of the experimental rig and the equations that govern the data reduction. Results for single-phase, evaporation, and condensation of the pure blend and CFC-12 are reported.

TEST FACILITIES

The test facility is capable of determining in-tube heat transfer coefficients for refrigerants during single-phase flow, evaporation, and condensation. The test rig has four main parts: a test section, a refrigerant loop, a water loop, and a water-glycol loop. The following paragraphs give a brief description of the four main parts of the rig. Detailed discussions of the experimental rig can be found in Schlager et al. [1,2]. A schematic drawing of the rig is shown in Figure 1.

The test section contains a horizontal smooth tube and a surrounding annulus. The inner tube in which the refrigerant flows is a 3.66 m long smooth tube with an outer diameter of 9.25 mm and an inner diameter of 8.0 mm. The annulus surrounding the tube is also a 3.66-m-long tube with an inner diameter of 17.2 mm. Water flows in the annulus counter to the refrigerant flow for the purpose of heating or cooling the refrigerant during testing. The refrigerant pressure in the test section is measured with a strain-gauge type pressure transducer with an experimental uncertainty of ±9 kPa. The pressure drop through the test section is measured with a stain-gauge type differential pressure transducer with an experimental uncertainty of ±0.2 kPa. A pair of thermocouples is located at the inlet and the exit of the refrigerant and water lines.

Refrigerant at a specific temperature, flow rate, and quality is supplied to the test section by the refrigerant loop. The refrigerant loop contains an after-condenser, a positive displacement pump, a bladder accumulator, a boiler, and a superheater. The positive displacement pump that is used does not require lubrication from oil addition, as in a compressor; thus, oil-free studies can be performed. The refrigerant flow rate to the test section is measured with a positive displacement flow meter with an experimental uncertainty of ±1%.

Water is supplied at a specific temperature and flow rate to the annulus of the test section by the water loop. The water loop consists of a centrifugal pump, a magnetic flow meter, and a heat exchanger. The temperature of the water entering the test section is controlled by the heat exchanger, which is supplied with warm or cold tap water depending on the temperature needed in the annulus. The water flow rate to the test section is measured with a magnetic flow meter with an experimental uncertainty of ±2%.

The water-glycol loop, which is used to condense the refrigerant exiting the test section, consists of a 209-L storage tank, a 17.5-kW refrigeration unit, a centrifugal pump, and a co-axial heat exchanger. The mixture is circulated through the co-axial heat exchanger in the refrigerant loop.

DATA REDUCTION

Because the blend is a near-azeotropic mixture the temperature and pressure relations in the saturation region change slightly [3]. Therefore, the enthalpy of vaporization and the qualities calculated are based on a constant pressure line through the saturation region. The following paragraphs describe the major equations used in the data reduction.

The refrigerant-side heat transfer coefficient is calculated from the overall heat transfer coefficient and the annulus-side heat transfer coefficient. The overall heat transfer coefficient is

$$U_o = \frac{Q_T}{A_o \cdot LMTD} \tag{1}$$

The heat transferred in the test section Q_T is calculated from an energy balance on the water side. The log mean temperature difference (LMTD) is determined from the annulus-side inlet and exit temperatures and the saturation temperatures at the inlet and exit of the test section. The heat transfer coefficient on the inside of the test tube can be calculated by knowing the overall heat transfer coefficient U_o, the water-side heat transfer coefficient h_o, and the ratio of the inside area A_i to the outside area A_o. The heat transfer coefficient on the annulus side of the test section was obtained by using a Wilson-plot technique [1]. Assuming that the resistance of the copper tube and the fouling effects are negligible, the heat transfer coefficient is

$$h_i = \frac{1}{\left(\frac{1}{U_o} - \frac{1}{h_o}\right)\frac{A_i}{A_o}} \tag{2}$$

The above equation determines an average heat transfer coefficient over the length of the tube. The inlet quality and quality change in the test section can be obtained from energy balances on the preheaters and the test section.

A propagation of error method was used to estimate the uncertainty in the experimental data [4]. Experimental uncertainties for the heat transfer coefficients of the blend ranged from ±8% to ± 13%. For example, during evaporation of the blend at mass flux of 400 $\frac{kg}{m^2 s}$, the estimated uncertainty in the heat transfer coefficient was ± 9%, while at a mass flux of 150 $\frac{kg}{m^2 s}$ the estimated uncertainty was ±3%. Estimated errors for the condensation heat transfer coefficients of the blend were similar to those given for evaporation. The experimental uncertainty in the reported refrigerant mass flux was ±3%, while the quality change had an experimental uncertainty of ±3.5%. Lubricant concentration accuracy is ±10% of the reported concentration.

TEST RESULTS

Experimentally determined heat transfer coefficients are reported for the blend during condensation, evaporation, and single-phase flow. Heat transfer coefficients are also reported for CFC-12 so that the relative performance of the blend can be assessed. The reported results are average heat transfer coefficients over the length of the test section. As mentioned earlier, the test tube is a horizontal smooth tube 3.66 m long with an inside diameter of 8.0 mm. The experimental heat transfer coefficients for the blend are also compared with the results from several theoretical correlations to determine which correlation best estimates the heat transfer coefficients of the blend.

Single-phase

Single-phase heat transfer coefficients were determined at various Reynolds numbers ranging from 22,000 to 37,000, with an average temperature of 24 to 27°C. Single-phase tests were conducted for two reasons. First, the heat transfer data are important for design because most condensers and evaporators operate with a single-phase region. Secondly, single-phase tests provide a check on the accuracy of the test facilities because single-phase heat transfer coefficients can be accurately predicted from correlations.

Figure 2 presents the single-phase heat transfer coefficients for the blend and CFC-12. The lines represent a least squares fit of the data points shown on the graph. When the results for the two refrigerants are compared at similar mass fluxes, the blend shows a 23% higher heat transfer coefficient than CFC-12.

The experimental results for the blend and CFC-12 were also compared to two different single-phase correlations, the Petukhov-Popov [5] and the Dittus-Boelter [6] correlations. Nusselt numbers for the blend are predicted to within 10% by both the Petukhov-Popov and the Dittus-Boelter correlations. For CFC-12, the Petukhov-Popov correlation predicted the Nusselt number to within 5%, while the Dittus-Boelter correlation predictions were within 25% of the experimental Nusselt number.

Evaporation

Evaporation tests for the pure blend were performed over a range of mass fluxes at three different pressures that correspond to average temperatures of 5°C, 10°C, and 15°C. The range of conditions for the evaporation tests are summarized in Table 1. The CFC-12 results, shown for comparison purposes, were taken under similar conditions.

Figure 3 presents experimentally determined evaporation heat transfer coefficients versus mass flux for the blend and CFC-12. The lines shown on the graph are least squares fit of the data at each temperature. The heat transfer coefficients for the blend increase with mass flux but show no significant change with temperature. When compared to CFC-12, also shown in Figure 3, the blend shows 12 to 25% higher heat transfer coefficients over the range of mass fluxes. A comparison of the heat transfer coefficients at flow rates more representative of those found in systems that employ the two refrigerants is discussed in a later section.

It should be noted that the above comparison is based on equivalent mass flux and quality change over a similar tube length for the two refrigerants. Therefore, because the enthalpy of vaporization is greater for the blend, the heat flux is greater at a particular mass flux for the blend than for CFC-12. The relationship between the higher heat flux and the increased heat transfer coefficient for the blend was estimated by using well-known correlations. The correlations estimated that 5 to 8% of the increase is caused by the higher heat flux for the blend.

The experimental heat transfer coefficients for the blend were compared to correlations by Shah [7], Kandlikar [8], and Chaddock and Brunemann [9]. The local heat transfer coefficients from the correlations were integrated over the length of the tube to obtain average heat transfer coefficients. The saturation properties of the blend used in the correlations were obtained from a constant pressure line through the saturation region. The liquid and vapor properties are, therefore, based on slightly different temperatures. The Shah and Kandlikar correlations predict the heat transfer coefficients to within ±18%, while the Chaddock-Brunemann correlation predicted heat transfer coefficients to within ±25%. It should be noted that the fluid-dependent factor in the Kandlikar correlation, adjusted to match the experimental data, was found to be 1.0. In comparison, the fluid-dependent factor for CFC-12 is 1.50 [8].

Condensation

Condensation tests were performed over the same mass flux range as the evaporation tests at pressures corresponding to average temperatures of 30°C, 40°C, and 50°C. The range of parameters for the condensation tests are shown in Table 2. Again, the results for similar tests with CFC-12 are also given in order to provide a base line of comparison.

Figure 4 gives the experimentally determined average heat transfer coefficients versus mass flux for the blend. The lines represent least squares fit of the data points at each temperature. The blend shows increasing heat transfer coefficients with mass flux and decreasing heat transfer coefficients with temperature. These trends closely resemble those for condensation of CFC-12, as is also shown in Figure 4. When the heat transfer coefficients for the two refrigerants are compared, the blend is higher than CFC-12 by 12 to 22% at the lower mass fluxes and increases of 20 to 30% at the higher mass fluxes. As mentioned in the evaporation discussion, the higher enthalpy of vaporization for the blend results in a higher heat flux. However, the higher heat flux does not affect this comparison because condensation heat transfer coefficients are not functions of heat flux.

Condensation heat transfer coefficients are compared with predicted heat transfer coefficients from the Shah [10], Traviss et. al. [11], and Cavallini and Zecchin [12] correlations. The predicted average heat transfer coefficients are obtained by integrating the local heat transfer coefficients from the correlations over the length of the tube. Except for the Shah correlation at the lowest mass flux, all correlations overpredict the heat transfer coefficients for the blend. Only the Shah correlation predicts the heat transfer coefficients within ±25% over the whole range of mass fluxes tested.

Comparison at equivalent cooling (heating) capacity

The experimental heat transfer coefficients for the blend and CFC-12 are compared at flow rates more representative of those that will be found in systems by forming the ratio of the heat transfer coefficients at similar cooling capacities for an evaporator and similar heating capacities for an condenser. The equivalent capacity ratios are formed from the least-squares fit of the evaporation and condensation heat transfer coefficients found in Figures 3 and 4. Specifically, this ratio is formed from heat transfer coefficients taken at equivalent values of mass flow rate times the enthalpy of vaporization of the refrigerant. Since the enthalpy of vaporization is higher for the blend, the heat transfer coefficient ratio is formed with the mass flow rate of the blend being significantly reduced compared to that of CFC-12. Figure 5 shows the equivalent cooling and heating capacity ratio at one condensation and evaporation temperature. The equivalent cooling capacity ratio is 0.82 to 0.92, while the heating capacity is 0.98 to 1.05. For the equivalent heating capacity case the ratio does not vary significantly with temperature; however, the ratio for the equivalent cooling capacity case does vary with temperature. For example, when the ratio of cooling capacities is formed at 5°C, which is more representative of evaporation temperatures found in actual refrigeration systems, the ratio increases to 0.92 to 1.0.

CONCLUSIONS

Heat transfer coefficients were determined for a refrigerant blend composed of 40% HCFC-124, 36% HCFC-22, and 24% HFC-152a. Evaporation heat transfer coefficients for the blend were 12 to 25% higher than CFC-12 when compared at equivalent mass fluxes. Condensation heat transfer coefficients for the pure blend were also higher that those of CFC-12. For example, at the lower mass fluxes the heat transfer coefficients for the blend were 12 to 20%, while at the higher mass fluxes this increased to 20 to 30% higher heat transfer coefficients. It should be noted that these comparisons are made at similar mass fluxes. The blend and CFC-12 were also compared at equivalent cooling capacities in an evaporator and equivalent heating capacities in an condenser. For the equivalent cooling capacity the ratio of the blend to CFC-12 heat transfer was 1.0 to 0.85, while the equivalent heating capacity ratio was 1.05 to 0.98.

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Table 1: Evaporation test conditions

Average temperature (°C)	5-15
Average pressure (MPa)	0.33-0.47
Mass flux ($\frac{kg}{m^2 s}$)	125-400
Quality in (%)	5-13
Quality out (%)	80-88

Table 2: Condensation test conditions

Average temperature (°C)	30-50
Average pressure (MPa)	0.73-1.26
Mass flux ($\frac{kg}{m^2 s}$)	125-400
Quality in (%)	80-88
Quality out (%)	10-18

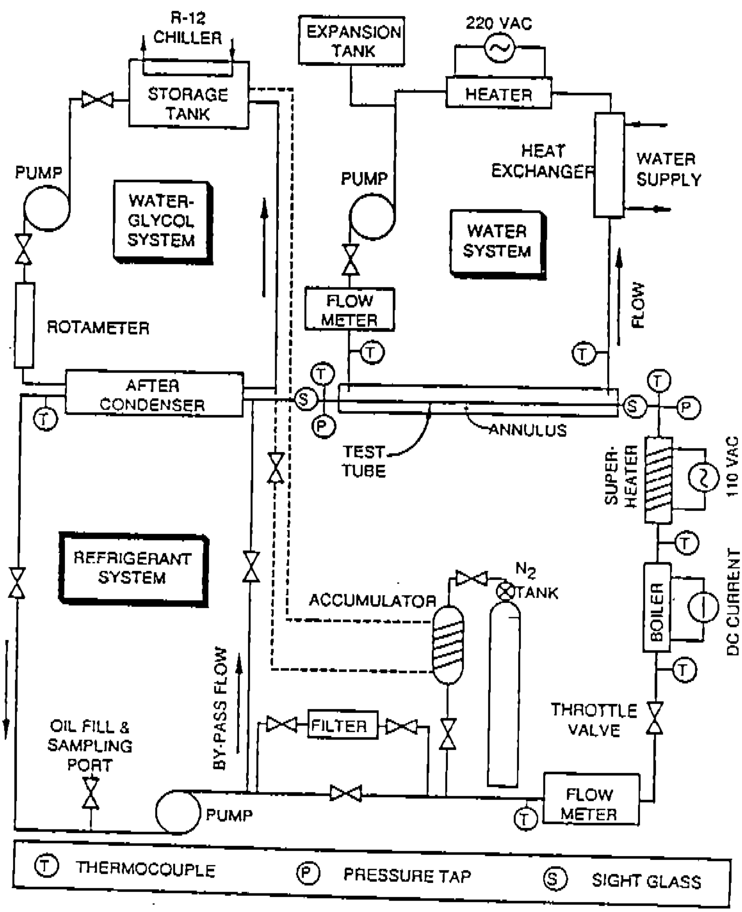

Figure 1: Schematic drawing of test facilities

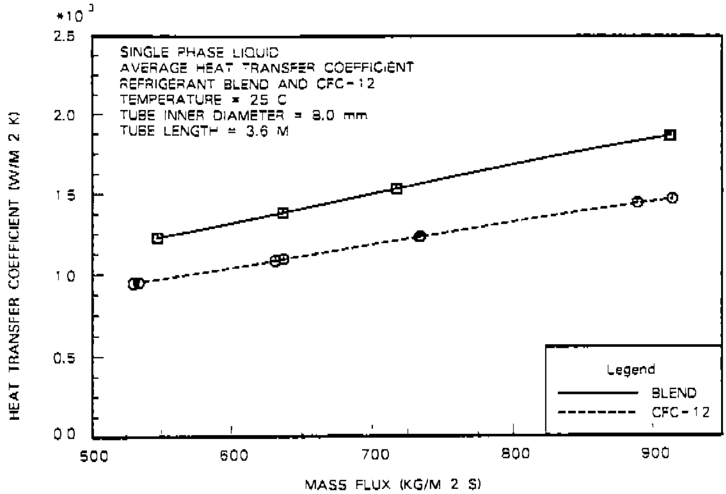

Figure 2: Measured single-phase heat transfer coefficients for the blend and CFC-12

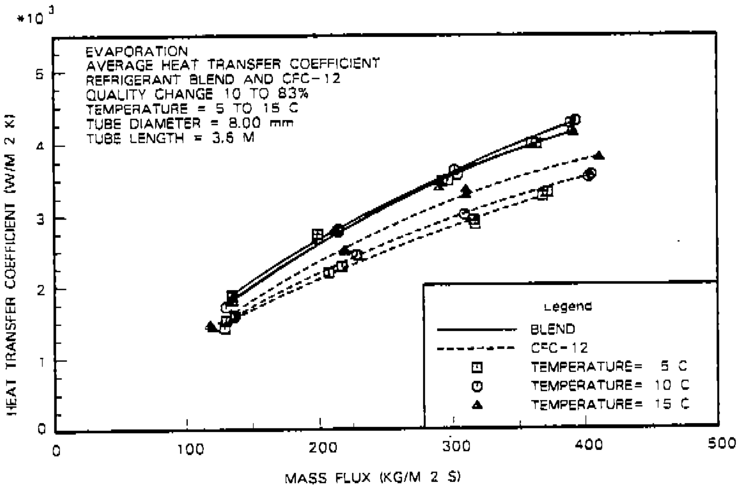

Figure 3: Measured evaporation heat transfer coefficients for the blend and CFC-12 at three temperatures

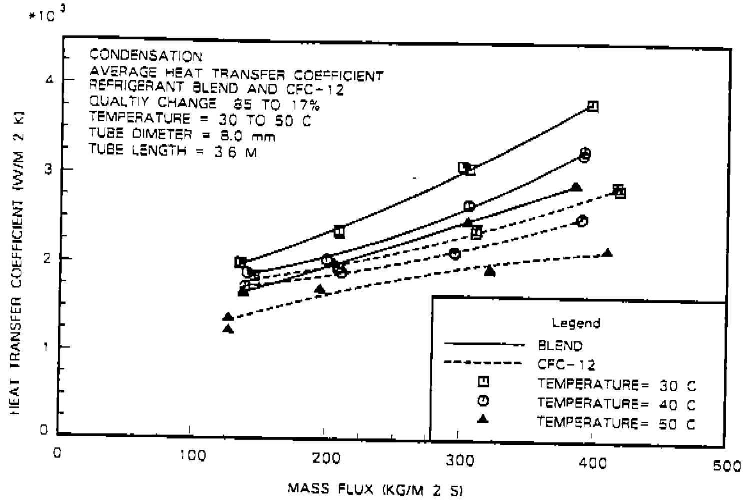

Figure 4: Measured condensation heat transfer coefficients for the blend and CFC-12 at three temperatures

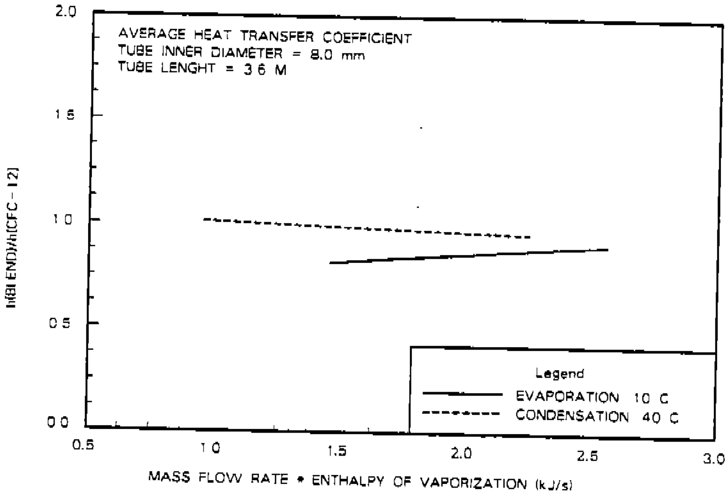

Figure 5: Ratio of blend-to-CFC-12 measured heat transfer coefficients for similar cooling and heating capacities